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Performance improvement in solar water heating systems—A review

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ABSTRACT

Solar energy is free, environmentally clean, and therefore it is accepted as one of the most promising alternative energy sources. The effective use of solar energy is hindered by the intermittent nature of its availability, limiting its use and effectiveness in domestic and industrial applications especially in water heating. Conversion of solar energy into thermal energy is the easiest and most used method. The efficiency of solar thermal conversion is around 70% but solar electrical direct conversion system has an efficiency of only 17%. Solar water heating systems are mostly suited for its ease of operation and simple maintenance. Many research papers revealed that the improvement on thermal efficiency of solar water heating systems resulted in techniques to improve the convection heat transfer. Solar water heating systems are classified into two broad categories as passive and active systems. Passive techniques have been used to improve the convective heat transfer. The techniques like insertion of twisted tapes and its geometry, etc., play a vital role to improve the performance of solar water heating systems. This review paper summarizes the previous works on solar water heating systems with various heat transfer enhancement techniques include collector design, collector tilt angle, coating of pipes, fluid flow rate, thermal insulation, integrated collector storage, thermal energy storage, use of phase change materials, and insertion of twisted tapes. This paper also discussed the methods to optimize and simulate the solar water heating systems to understand flow and thermal behavior in solar collectors that would lead to the improvement of the thermal performance of solar collectors.

Contents

1. Introduction

In recent years solar energy has been strongly promoted as a viable energy source. One of the simplest and most direct applications of this energy is the conversion of solar radiation

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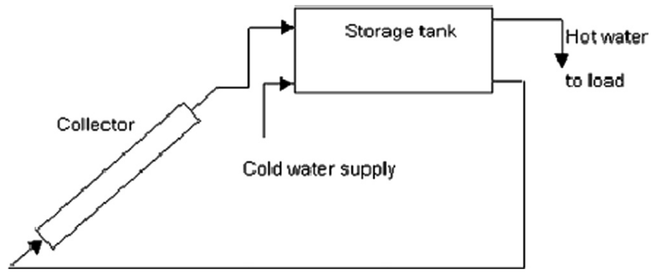

Fig. 1. Schematic diagram of a typical thermosyphon solar water heating system.

into heat. Solar energy is recognized as one of the most promising alternative energy options. On sunny days, solar energy systems generally collect more energy than necessary for direct use. Therefore, the design and development of solar energy storage systems, is of vital importance and nowadays one of the greatest efforts in solar research. These systems, being part of a complete solar installation, provide an optimum tuning between heat demand and heat supply. Hence way that the domestic sector can lessen its impact on the environment is by the installation of solar flat plate collectors for heating water.

A Solar Water Heating System (SWHS) is a device that makes the available thermal energy of the incident solar radiation for use in various applications by heating the water. Hot water is essential both in industries and domestic applications. It is required for taking baths, washing clothes and utensils, and other domestic purposes in both the urban and rural areas. Hot water is also required in large quantities in hotels, hospitals, hostels, and industries such as textile, paper and food processing, dairy, and edible oil. The SWHS consists of solar thermal collectors, water tanks, interconnecting pipelines, and the water, which gets circulated in the system. Fig. 1 illustrates the typical thermosyphon solar water heating system [1]. Solar radiation incident on the collector heats up the tubes, thereby transferring the heat energy to water flowing through it. In brief, solar energy incident on the flat-plate collector is absorbed by the black-chrome coated copper plate and thereby heats the water in the riser tubes which circulates due to density difference, i.e. the thermosyphon effect. Solar Water Heating systems are grouped into two broad categories as passive and active solar water heating systems. The passive solar water heating systems generally transfer heat by natural circulation as a result of buoyancy due to temperature difference between two regimes; hence they do not require pumps to operate. They are the most commonly used solar water heating systems for domestic application. Active solar water heating systems have electric pumps, valves, and controllers to circulate water or other heat-transfer fluids through the collectors.

The active solar water heating systems generally have higher efficiencies, their values being 35–80% higher than that of the passive systems [1]. It is more complex and expensive. Accordingly, it is most suited for industrial applications where the load demand is quite high. On the other hand, the passive systems are less expensive and easier to construct and install which is more suitable for domestic applications where demand is low or medium.

The thermal performance of SWHS is influenced by inlet water temperature, solar irradiance, ambient temperature, flow rate, inclination of the flat-plate collector, height of the hot water tank, wind speed, relative humidity etc. The storage tank too plays an important role in accumulating the energy obtained from solar collector. The performance of the SWHS largely depends on the collector's efficiency for capturing the incident solar radiation and transferring it to the water. Generally the parameters that influence the thermosyphon effect are thermo-physical properties of liquid and the temperature of the surface in contact with liquid. With today's SWHS, water can be heated up to temperatures of 60 °C to 80 °C. Heated water is collected in a tank which is insulated to prevent heat loss. Circulation of water from the tank through the collectors and back to the tank continues automatically due to the thermosyphon principle.

Many of the industries use hot water in the range of 70–90 °C. These include dairy, food processing, textiles, hotels, edible oil, chemical, marine chemicals, bulk drug, breweries, and distilleries. These requirements are presently met primarily by combustion of fossil fuels like coal, lignite, and fuel oil. Solar energy, being abundant and widespread in its availability, makes it one of the most attractive sources of energies. Tapping this energy will not only help in bridging the gap between demand and supply of electricity but shall also save money in the long run. According to the Ministry of New and Renewable Energy (MNRE), Government of India, a 100 l capacity SWHS can replace an electric geyser for residential use and may save approximately 1500 units of electricity, annually, under Indian conditions [2]. Thus, a typical family can save 70–80% on electricity or fuel bills by replacing its conventional water heater with a solar water heating system. It has also been estimated that a 100 l per day (lpd) system (2 m^2 of collector area) installed in an industry can save close to 140 l of diesel in a year. So also, usage of solar water heater to supply preheated boiler feed water can help saving 70–80% of fuel bills.

Reduction of pollution and preservation of environmental health are some of the co-benefits of this technology. This is probably why the use of solar energy for water heating has become one of the largest applications of solar thermal systems today. Based on the above mentioned equivalence (100 lpd system saves 1500 units (kW h) of electricity), it is estimated that in generating the same amount of electricity from a coal-based power plant, 1.5 t of CO_2 is released into atmosphere annually. One million SWHSs installed in homes will, therefore, result in reduction of 1.5 million tonnes of CO_2 emission into the atmosphere. Clearly, SWHS is one of the most cost effective, viable, and sustainable options available for hot water generation today. The maximum Solar intensity/Heat flux for Indian climate is taken as (Salem, Tamilnadu, India) is 702.85 W/m^2.

2. Heat transfer enhancement techniques in solar water heating systems

Topic on the research of solar energy has become a matter of great concern due to energy crisis all over the world. The direct applications of solar energy (i.e. thermal application of solar energy) are simpler and more feasible application compared to indirect applications (i.e. photoelectric application) to generate electricity by using solar radiation. Flat plate collector is the central component of any solar water heating system. The efficiency of a solar water heating system is based on the performance of flat plate collector. Flat-plate solar collectors are the devices which absorb the solar radiation, transform it into heat, and to heat passing media (usually air, water, or oil). Flat-plate solar collectors are simpler than concentrating collectors to be used in domestic and industrial needs, which are constructed with the blackened absorber to transfer the absorbed energy to the flowing medium, transparent cover to reduce convection and radiation losses to atmosphere, and back and side insulation to reduce conduction losses. Hence, the most of the research works have been focused on the performance improvement of flat plate collector. The characteristics of thermosyphon systems are based on the absorber plate and its design, selective coatings, thermal insulation, tilt angle of the collector, and working fluids, etc.. Several designs of solar collectors have been analyzed by the researchers to enhance the thermal behaviour of thermosyphon systems.

2.1. Absorber plate design

Shariah et al. [3] have theoretically studied the effect of the thermal conductivity of the absorber plate of a thermosyphon solar water heater on the characteristic factors and solar fraction by the use of the TRNSYS computer program. Results were found that the collector efficiency factor and heat removal factor have strong dependence on the thermal conductivity of the absorber plate. The results showed that there is almost no advantage in using copper in lieu of aluminium unless other factors such as corrosion problems or health hazards could affect the choice of the material for the absorber plate. Runsheng et al. [4] have constructed and tested two sets of thermosyphon domestic solar water heating systems to investigate the effects of water temperature in the storage tank in terms of outlet water temperature. Experimental and theoretical results showed that with the increase of water temperature in the tank of a thermosyphon domestic solar water heating systems, the outlet water temperature is increased. Results by simulations showed that the collector-tank height difference and the thermal emissivity of absorbers had significant effects on the freeze protection of collectors in terms of outlet water temperature. Comparative studies have made on the thermal performance of water-in-glass evacuated tube solar water heating systems with different collector tilt angles by Runsheng et al. [5]. Results showed that the daily thermal efficiency of solar water heating systems was almost independent of the climatic conditions as a result of lower heat loss from solar tubes to the ambient air. Also it was found to maximize the annual heat gain of such solar water heating systems, the collector should be inclined at a tilt-angle for maximizing its annual collection of solar radiation.

Chien et al. [6] have experimentally and theoretically investigated a two-phase thermosyphon solar water heater. The thermal resistance capacitor method was provided to build the theoretical model for the system and obtained the improved strategies of the overall system. The system parameters include the different heating powers and the tilt angles of the heater. The experimental results showed that the best charge efficiency of the two-phase thermosyphon solar water heater is 82%. The charge efficiency decreases not more than 5% when the tilt angle of the system is less than 15°. Effect of aspect ratio on the collector efficiency of sheet-and-tube solar water heating systems has been investigated theoretically by Yeh et al. [7]. It is observed that the collector efficiency increases with increasing collector aspect ratio for constant collector area and distance between tubes.

Alireza et al. [8] have investigated the impact of heat enhancement devices on the thermal performance of a flat-plate solar collector. Different passive heat enhancement devices that include twisted strip, coil-spring wire and conical ridges were studied. The conclusion made that due to the significant damping of shear-produced turbulence by buoyancy forces, the applied passive methods based are ineffective in augmenting heat transfer to the collector fluid in flat-plate solar collectors. Ho et al. [9] have studied a theoretical prediction of the performance of a double-pass sheet-and-tube solar water heater with external recycle and comparison with that of a conventional type collector. Results showed that the recycle effect can effectively enhance the collector efficiency compared with that in a single-pass device with the same flow rate. Ho et al. [10] have further investigated the effects on collector efficiency of a double-pass sheet-and-tube solar water heater with internal fins attached under various arrayed density. The theoretical prediction shows that the higher collector efficiency was obtained under the suitable designing and operating conditions. Considerable improvement in collector performance is obtained by employing a recyclic operation with fins attached and under various arrayed density, instead of employing a single-pass flat-plate device. Taherian et al. [11] have experimentally validated the dynamic simulation of the flat plate collector of a closed thermosyphon solar water heater with horizontal mantle-type storage tank in certain weather conditions. By the simulation the mean efficiency of 68% was obtained. It has been found that the storage tank is designed such that the incoming fluid to the collector is at a temperature close to that of the surrounding. A number of heat extraction methods from all-glass evacuated tubes have been developed by Morrison et al. [12] and the water-in-glass concept has been found to be the most successful due to its simplicity and low manufacturing cost. Factors influencing the operation of water-in-glass collector tubes were discussed and a numerical study of water circulation through long single-ended thermosyphon tubes was presented. Preliminary numerical simulations have shown the existence of inactive region near the sealed end of the tube which might influence the performance of the collector.

2.2. Coatings of pipes

The investigation and preparation of new solar selective paints for solar collectors coating has attracted much attention in many developing countries. The advantages of using electro deposited chrome selective surfaces and other performance of the solar water heating systems are evaluated by Santamouris et al. [13]. The results showed that the use of chrome selective coatings is economically sound. Arif [14] conducted a test at the solar energy centre combined with the Indian Institute of Technology, Delhi. The results revealed that even for low temperature applications of 50 °C and above, Solchrome solar selective coatings and Solchrome solar selective coating fin and tubes increase the thermal efficiency of solar collectors by more than 30%, as against the use of black paint or any other coating. The development of the Cu–Ni alloy coating as a selective surface for solar energy use was reported by Tharamani et al. [15]. Effects of electrolyte concentration and operating parameters on the appearance and optical properties of the coating were studied. Results showed that the coating surfaces had the high absorptance and low emittance rates. A novel and affordable solar selective coating exhibiting higher solar absorption efficiency compared to the commercial black paint coating used in ordinary solar water heating systems. SWHS with coating has been developed by Ehab [16]. The coating is fabricated by embedding a metallic particle composed of a nickel–aluminium (NiAl) alloy into the black paint. The applicability of the coating in a real thermosyphonic solar water heating systems was evaluated throughout the year. It was found that the coating showed better performance compared to the untreated black paint by an average of 5 °C over a period of 1 year. Tae June et al. [17] found a transparent glass heater material coated with single-walled carbon nanotube film. The heating systems have an optical transparency above 95% in visible light. Their performance was investigated by measuring their heating/cooling characteristics and thermal resistance. The stability and reliability of the heater were also investigated. Results showed that thermal energy was more efficient that ordinary paint coated surface.

2.3. Flow analysis in solar water heating systems

Chuawittayawuth et al. [18] presented the details of experimental observations of temperature and flow distribution in a natural circulation solar water heating system and compared with the theoretical models. The measured profile of the absorber temperature near the riser tubes conforms well with the theoretical models. The values at the riser tubes near the collector inlet are found to be generally much higher than those at the other risers on a clear day, while on cloudy days, these temperatures are

uniform. The temperature of water in the riser depends on its flow rate. Arvind et al. [19] obtained an analytical expression for the water temperature of an integrated photovoltaic thermal solar water heater under constant flow rate hot water withdrawal. Analysis is based on basic energy balance for hybrid flat plate collector and storage tank, respectively, in the terms of design and climatic parameters. Further, an analysis has also been studied for hot water withdrawal at constant collection temperature. It is observed that the daily overall thermal efficiency of an integrated photovoltaic thermal solar water heater system increases with increase constant flow rate and decrease with increase of constant collection temperature. This type of thermal analysis is used to design the hot water systems based on flow rate and number of collectors.

Morrison et al. [20] evaluated the characteristics of water-in-glass evacuated tube solar water heating systems including assessment of the circulation rate through single ended tubes. A numerical model of the heat transfer and fluid flow inside a single ended evacuated tube have been developed assuming no interaction between adjacent tubes in the collector array. For a specific collector configuration, circulation flow rate through the tubes is influenced by two factors, namely the radiation intensity falling onto the absorber surface and the temperature of the storage tank. Flow measurement using Particle Image Velocimetry (PIV) has been undertaken to validate the numerical model. It was found that the circumferential heat distribution to be an important parameter influencing the flow structure and circulation rate through the tube. It was also reported that a separate correlation needs to be developed if a concentrating reflector is incorporated into the collector.

2.4. Solar water heater using heat pump

Wongee et al. [21] have investigated the performance of solar domestic hot water systems manufactured with heat pipes for different working fluids. It was reported that the system performance was relatively insensitive to the selection of the working fluid. During the period of low solar radiation, the system with the heat pipe has shown uniform temperature distribution compared to that of thermosyphon case. However, no appreciable differences are observed for the cumulative system efficiency. A new solar water heater system was developed by Natthaphon et al. [22], that used a solar water pump instead of an electric pump. The solar water pump was powered by the steam produced from a flat plate collector. Therefore, heat could be transferred downward from the collector to a hot water storage tank. The economic justification showed that this system was comparable to a conventional one. The system may be further improved by Sterling et al. [23]. One indirect-style solar assisted heat pump design was modeled using the TRNSYS software and compared to a traditional solar domestic hot water system and an electric domestic hot water system. The result proved that the dual tank indirect-style solar assisted heat pump system to be the most energy efficient and had the lowest annual operating cost. Li et al. [24] tested and analyzed a direct expansion solar-assisted heat pump water heater with rated input power 750 W. The performance of the first system with rated input power 750 W was shown through experimental research in spring and thermodynamic analysis and some suggestions for the system design optimization are proposed. Then, a small-type system with rated input power 400 W with new type collector/evaporator was built, tested, analyzed and then compared with the first system. Under similar running cost expected, the smaller system with lower capital cost and smaller collector/evaporator area has the advantage so as to integrate it with building's roof.

A theoretical study on forced circulation solar water heating system with flat-plate collector that provides hot water requirements of a single-family house has been carried out by Alireza et al. [25]. All the necessary design parameters were studied and the optimum values are determined using TRNSYS simulation program. Two sets of simulations were conducted. The first set was conducted to determine the optimum values of the system parameters and the second set was conducted to determine the optimum values of the collector design parameters. The annual solar fraction was considered as the optimization parameter. The results showed that by utilizing solar energy, the designed system could provide 83–97% and 30–62% of the hot water demands in summer and winter, respectively. It was also determined that even a locally made non-selective-coated collector can supply about 54% of the annual water heating energy requirement by solar energy. Ogueke et al. [26] presented the review of solar water heating systems for domestic and industrial applications. Their performances, uses and applications, and factors considered for their selection are reported. The active systems generally have higher efficiencies, their values being 35–80% higher than that of the passive systems.

2.5. Integrated collector tank solar water heater

Most solar water heater designs can be categorized into three groups: forced circulation, natural convection and integrated collector-storage. The integrated collector-storage solar water heater (ICSSWH) is relatively simple in design and operation. The cost of ICSSWH system is comparatively lower than that of other solar water heater designs and it was found by Kalogirou [27]. The integrated collector cum storage solar water heating systems which combine solar collector and water storage tank in one unit offers more cost effective and have less maintenance and it was reported by Garg et al. [28]. Hence this type of low cost integrated solar water heating systems is more affordable among house holders particularly for a small size family to meet hot water requirements for various purposes. Chaurasia et al. [29] have suggested to introduce transparent insulation material in integrated storage solar water heating systems. The use of transparent insulation material in such water heating systems increases its efficiency and provides hot water at higher temperature as compared to conventional integrated storage solar water heater with glass glazing. The ICSSWH, by its combined collection and storage function suffers substantial heat losses to ambient, especially at night-time and non collection periods. To be viable economically, the system has evolved to incorporate new and novel methods of maximizing solar radiation collection whilst minimizing thermal loss [30]. Advances in Integrated Collector Storage (ICS) vessel design have included glazing system, methods of insulation, reflector configurations, use of evacuation, internal and external baffles and phase change materials (Fig. 2).

A study with a suitable artificial neural network (ANN) and TRNSYS are combined in order to predict the performance of an ICS prototype, was presented by Souliotis et al. [31]. The suggested methodology of combining ANNs and TRNSYS can be used to

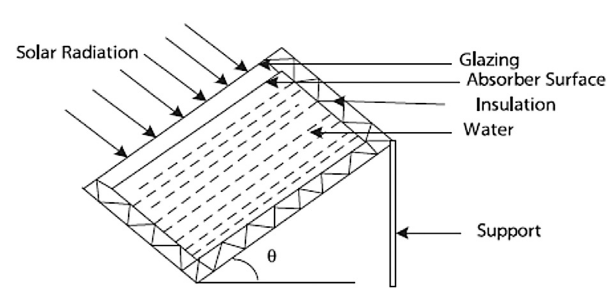

Fig. 2. Cross-sectional view of rectangular integrated collector-storage solar water heater.

model systems, which are difficult to model analytically, or their model is not available. The introduction of corrugated absorber surface over plane surface in collector/storage type solar water heater is an option to get more useful heat at higher temperature. An investigation was reported of the thermal performance of an integrated solar water heater with a corrugated absorber surface by Rakesh et al. [32]. For most part of the day the proposed solar water heater is having higher temperature of water than the plane surface.

2.6. *Use of phase change materials in solar water heating systems*

Thermal energy storage systems which keep warm and cold water separated by means of gravitational stratification have been found to be attractive in low and medium temperature thermal storage applications due to their simplicity and low cost. This effect is known as thermal stratification. This system stores sensible heat in water for short term applications. Hassan E. S. [33] has reviewed the basic concepts, systems design, and the latest developments in the sensible and latent heat thermal energy storage. Vikram et al. [34] have been studied the feasibility of storing solar energy using Phase Change Materials (PCMs) and utilizing this energy to heat water during night time. This ensures that hot water is available throughout the day. The system consists of two simultaneously functioning heat-absorbing units. One of them is a solar water heater and the other a heat storage unit consisting of PCM (paraffin). Experimental results indicated that thermal characteristics of the PCM and configuration of the PCM storage unit could result in advantageous control of the water temperature rise and drop during both day and night time was reported by Sefa et al. [35]. A thermal energy storage (TES) unit is designed, constructed and integrated with constant temperature bath and or solar collector to study the performance of the storage unit by Nallusamya et al. [36]. The TES unit contains paraffin as PCM filled in spherical capsules, which are packed in an insulated cylindrical storage tank. The water used as heat transfer fluid to transfer heat from the constant temperature bath/solar collector to the TES tank also acts as sensible heat storage (SHS) material. It was found that the combined storage system gives better performance than the conventional SHS system. Investigation on thermal energy storage incorporating with and without the use of PCM in solar water heater has been taken up by Anant et al. [37]. A better thermal performance of solar water heater can be achieved with a phase change material having high latent heat and large surface area for heat transfer. Muhsin et al. [38] have reported that adding PCM modules at the top of the water tank would give the system a higher storage density and compensate heat loss in the top layer. The thermal performance of trapezoidal-shaped solar collector assembly was influenced by thermal stratification. It has been studied experimentally by Cruz et al. [39]. This trapezoidal cross-section induces thermal stratification in the water storage and provides sufficient energy storage to meet the daily hot water demand. The results revealed that total energy-saving by this trapezoidal design were found to be around 30–70%. Ouzzane and Galanis [40] have numerically analyzed heat transfer in a tube with a longitudinal fin. This system is modeled as a flat-plate collector. The heat flux (solar radiation) was incident on the top surface. The bottom surface was insulated. The results showed that most of the heat energy is conducted to the fluid in the bottom half of the tube.

2.7. *Insertion of twisted tapes in solar water heating systems*

The use of twisted tapes in solar water heater to improve the thermal performance has been experimentally verified by Kumar and Prasad [41] in forced circulation mode for various twist ratios. It was concluded that twisted tapes could be inserted inside the flow tubes in solar water heating systems for enhancing heat transfer rate. Also it was stated that decreasing values of the twist-pitch to tube diameter ratio lead to increasing values of heat transfer rate, and the pressure drop as well. The heat transfer and pressure drop in twisted tape collectors have been found to increase by 18–70%, and 87–132%, as compared to plain tube collectors within the range of investigated parameters (twist ratio 3–12) (Fig. 3).

Influence of helical tapes inserted in a tube on heat transfer enhancement is studied experimentally by Smith et al. [42]. A helical tape is inserted in the tube with a view to generate swirl flow that helps to increase the heat transfer rate of the tube. The regularly spaced helical tape inserts with twist ratio of 0.5 yields the highest Nusselt number which is about 50% above the plain tube (Fig. 4).

Alireza et al. [43] have investigated the impact of heat enhancement devices on the thermal performance of a flat-plate solar collector. Different passive heat enhancement devices such as twisted strip, coil-spring wire and conical ridges were studied. It was concluded that due to the significant damping of shear-produced turbulence by buoyancy forces, the applied passive methods (based on the enhancement of shear-produced turbulence) are ineffective in augmenting heat transfer to the collector fluid in flat-plate solar collectors. Experimental investigation of heat transfer and friction factor characteristics of thermosyphon solar water heater fitted with helical twisted tape of different twist ratios was performed and presented by Jaisankar et al. [44].

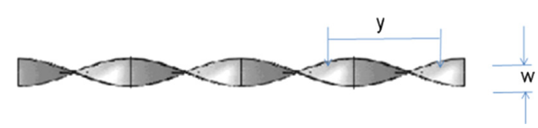

Fig. 3. Twisted tape, Twist ratio $Y=y/w$.

Fig. 4. Helical tape is inserted in the tube.

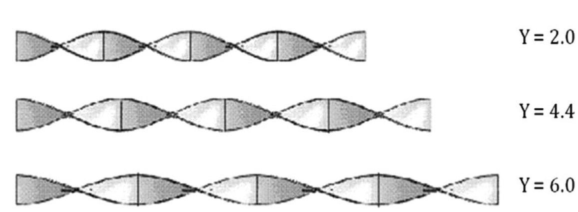

Fig. 5. Twisted tapes with various twist ratios.

The results showed that the friction factor increases with twisted tape inserts and also there is a significant increase in the heat transfer which ultimately increases the efficiency of the system (Fig. 5).

Experimental investigations of heat transfer and friction factor characteristics of circular tube fitted with trapezoidal -cut twisted tape for twist ratios 6.0 and 4.0 carried out for turbulent flow by Murugesan et al. [45]. Heat transfer coefficient and friction factor increases with the decrease in twist ratio compared with plain tube. Trapezoidal -cut twisted tape for twist ratios 6.0 and 4.0 augment the heat transfer rate 27 and 41.8% higher than the plain tube (Fig. 6).

Experimental investigation of heat transfer, friction factor and thermal performance of twisted tape solar water heater with various twist ratios has been conducted and the results are compared with plain tube collector for the same operating conditions with Reynolds number varied from 3000 to 23,000.

Jaisankar et al. [46] have experimental studied the heat transfer and friction factor characteristics of thermosyphon solar water heater with left–right helical twisted tape inserts. It was concluded that the overall thermal efficiency of the system is more for left–right twists when compared to helical tapes. Further, Kumar and Prasad [47] have developed and tested the modified solar water heater having twisted tape (artificial roughness) inserted inside the tubes along the plain one (Fig. 7).

Naga et al. [48] carried out the experiments for plain tube with/without twisted tape insert at constant wall heat flux for different mass flow rates. The twisted tapes of three different twist ratios (3, 4 and 5) each with five different widths (26-full width, 22, 18, 14 and 10 mm) respectively were taken for the experiments. It was concluded that reduced-width tape inserts were seen to be attractive for enhancing turbulent flow heat transfer in a horizontal circular tube to enhance the heat transfer and savings in pumping power and also in tape material cost. The heat transfer characteristics and friction factor results of the horizontal double tubes with twisted wire brush insert were presented by Paisarn et al. [49]. The effect of twisted wires density, inlet fluid temperature, and relevant parameters on heat transfer characteristics and friction factor were considered. Due to the presence of swirl flow, the convective heat transfer obtained from the plain tube with twisted wires brush insert is higher than that with the plain tube without twisted wires brush. Dr. Akeel Abdullah [50] has found that the Conical-ring with or without twisted tapes could be inserted inside the flow tube for enhancing heat transfer rate by increasing the pressure drop. The results showed that the heat transfer coefficient and friction factor increased with the decrease in twist ratio compared with plain tube. The tube having combined conical-ring and twisted tape insert gave higher heat transfer rates than that tube fitted with conical-ring alone (Fig. 8).

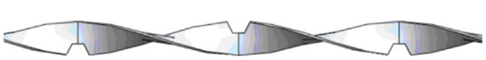

Fig. 6. Trapezoidal-cut twisted tape.

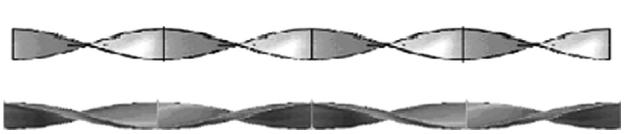

Fig. 7. Various designs of twisted tape insert (helical, left–right).

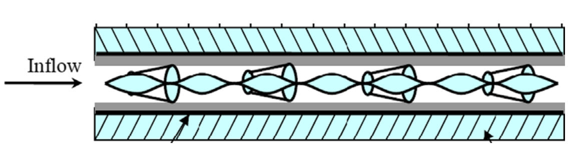

Fig. 8. Test tube fitted with conical-ring and twisted tape insert.

Fig. 9. Cylindrical solar water heater.

2.8. Cylindrical solar water heater

Proper design of solar water heating system is important to assure maximum benefit to the user, especially for a large system. Designing a solar hot water system involves appropriate sizing of different components based on predicted solar insolation and hot water demand. A cylindrical collector-cum-storage type solar water heater has been designed, developed and tested by Nahar et al. [51]. The year round performance has been carried out and reported. The results revealed that the heater received approximately 30% more radiation as compared to a flat surface. The heater can provide 50 l of hot water at 50–60 °C in the afternoon and a temperature of 35 °C can be retained till the next day for early morning use. The economics of the heater has been worked out and it has been found that the cost can be recovered within one year. An unsteady analysis of a cylindrical solar water heater has been performed by Saroja et al. [52]. The physical parameters which govern the physical system were identified. The governing equations have been solved using the fourth order Runge–Kutta method for different values of the parameters. A good agreement between the numerical and experimental results has been obtained. The analysis was useful to understand the thermal behavior of cylindrical solar water heater. Hussain [53] designed and manufactured a cylindrical solar water heater. The maximum efficiency during the experimental period was found to be 41.8%. This reveals a good capability of the system to convert solar energy to heat which can be used for heating water. A major advantage of this system is that it is not necessary to direct it to the sun because of its circular shape, whereas the flat plate collector should always be directed to face the sun with a certain tilted angle to get the best efficiency. An economic analysis has revealed that the cylindrical solar water heater compared with the flat plate collector was cost effective (Fig. 9).

2.9. Simulation techniques in solar water heating systems

The performance prediction of thermosyphon solar water heater was analyzed by Soteris et al. [54] by using Artificial Neural Networks. It was concluded that it is possible to train a suitable neural network to model a thermosiphonic solar domestic water heating system which can be used to predict the performance of the system under any weather conditions. The advantages of this approach by using Artificial Neural Network (ANN) compared to the conventional algorithmic methods were the speed of calculation, the simplicity and the capacity of the network to learn from examples and thus gradually improve its potential and performance. An experimental solar hot water generator has been constructed and tested by Cuma et al. [55] in order to establish the thermodynamic efficiency of the system by using ANN. With ANN, by using a well trained network, useful energy, mass flow rate and other parameters can be obtained without doing additional experiments. The results showed that the system has proved 40% efficiency. Solar radiation is highly dependent on site location and regional climatic conditions. The Geographical

Information System (GIS) method for the estimation of solar potential for water heating, presented by Voivontas et al. [56]. The estimated method was used to account the geographic distribution of solar radiation, the market for solar thermal systems, used to identify the allocations of the expected energy savings and profits from a large-scale deployment of solar domestic hot water systems. From the results the adoption of the GIS environment provided some new spatial insight on each stage of the analysis of solar water heating systems. Current flat plate solar water heating systems overproduce slightly in summer and have poor performance in winter at the time of maximum load. They use an expensive absorber plate over the entire absorbing aperture of the collector and fail to use the backside of the absorber. They often have under insulated tanks and are not optimized as integrated systems. Mills et al. [57] have described a design approach taken to use existing commercial flat plate absorber and tank components in a new way to maximize solar contribution and minimize material usage in the construction of the system. A methodology is proposed by Govind N et al. [58] to determine the design space for synthesis, analysis, and optimization of solar water heating systems. The proposed methodology was helpful in clear understanding of the behavior of the system with different storage volumes and collector areas supplying a specified load, thus revealing constraints and flexibilities. The proposed methodology could be applied to many different solar thermal configurations.

3. Conclusion

Solar water heating systems have been exhaustively reviewed. It gives overview of the developments in the areas of technologies to improve the performance of the existing system and also to design a new system. The following are the major salient points from this study.

- Most of the research works have been conducted in forced circulation mode only. The research works in natural circulation solar water heating systems should be improved.
- Thermal energy storage systems can be an alternative option to the present day solar water heating systems with less complicated design and cost effectiveness. The latent heat thermal energy systems are a commercially viable option for solar heat energy storage with further research in this area.
- The enhancement of heat transfer in the solar collector with twisted tape is found to be better than the conventional plain tube collector. In solar water heating systems twisted tape has been used as one of the passive techniques to augment the heat transfer. Twisted tape has been used in heat exchangers but their applications are limited in solar water heating systems.
- Even though theoretical and experimental studies are available to find out the performance of solar water heating systems, detailed experimental studies showing the temperature profiles are few. Detailed investigation of flow and thermal behavior in solar collectors should be done to understand the complex dynamics that would be very useful to improve the thermal performance of solar collectors.
- Because of more cost effective and simplicity, more number of research works must be initiated to analyze the behavior of thermosyphon solar water heating system to improve better performance.

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